Chapter 5:

Tables and Figures

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Table 5-1. Location of various analyses of concentrations and metals mass transport during the Gold King plume movement.

Analysis Focus	Informs	Where To Find	Where to Find
Longitudinal and temporal patterns of metal concentrations	Exposure potential for various uses of water (aquatic life, irrigation and livestock, recreation)	Observations, modeled plume at locations	Chapter 5
Metals Mass (kg) (Concentration X Flow)	Enables tracking fate of Gold King metals: Sequestration to streambed	Modeled Plumes	Chapter 6

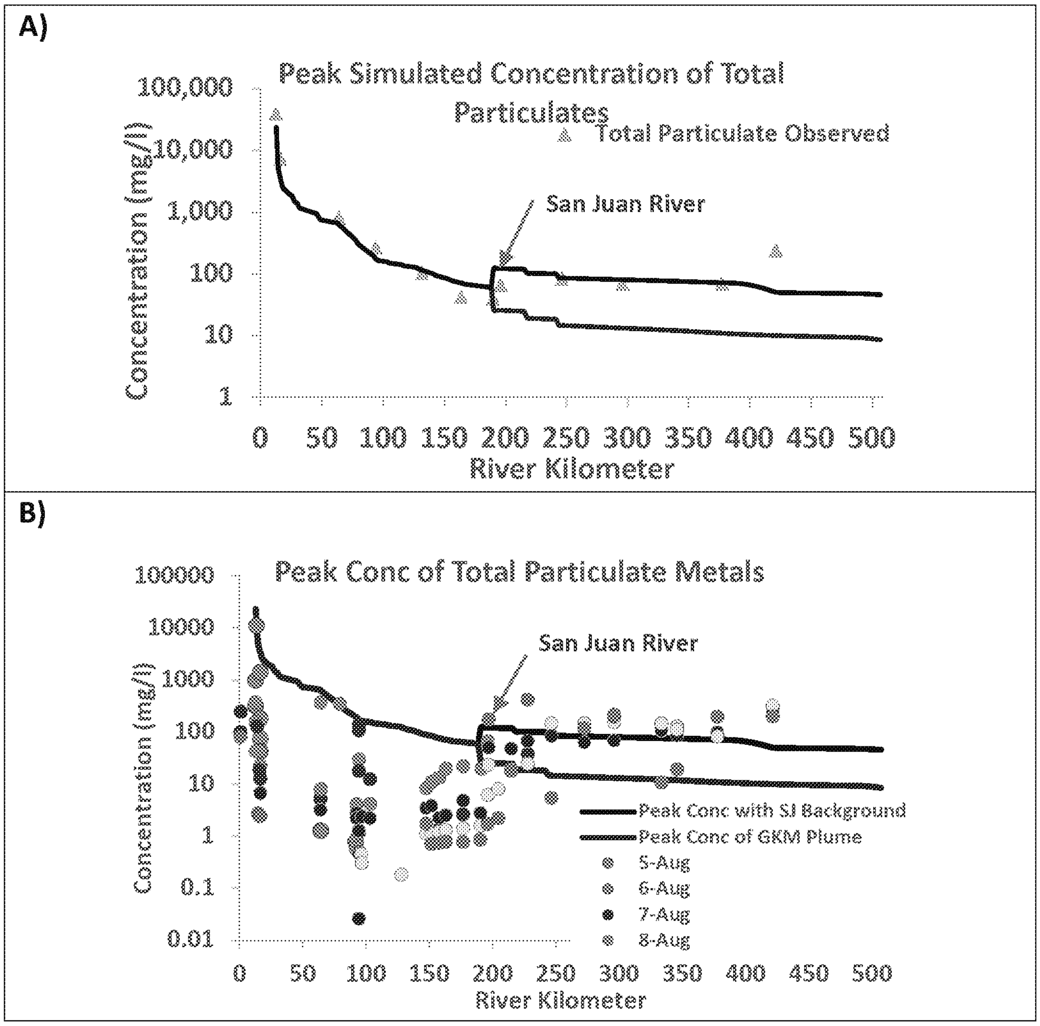

Figure 5-1. Simulated peak total metal concentrations plotted versus river distance. The two lines presented here represent two simulations of the Gold King Mine release. The lower/red line represents a simulation of the peak total metal concentrations due solely to the release, as if flowing in distilled water, and all incoming boundaries have zero concentrations. The upper/black line is a simulation of background concentrations in the San Juan River upstream of the confluence with the Animas River. This results in an uptick in concentration. Where the Animas joins the San Juan background metals load increase with sediment. (Background concentrations in the Animas were near zero and not included.) A) Total particulate observed peak concentrations are presented as calculated using the empirical method detailed in XXXX. Notice the increase in concentrations upon reaching the San Juan River. B) Observed concentrations of samples taken from August 5 to 9, 2016. These do not represent peak concentrations, simply the concentrations of samples taken at these distances at these times. These times may represent any hour on that day. It is unclear if these are before, during, or after the plume. However, it seems reasonable that the high observed concentrations are representative of the plume as it passed. There is a noticeable uptick in concentration upon reaching the San Juan River that continues for the length of the river. For the two simulations, the simulations match well with the observed, showing how the processes incorporated in our model (dilution, dispersion, settling) capture the changes in concentration. These two figures suggest the importance of the influence of incoming concentrations from the San Juan River to match the observed concentrations along the San Juan River. The uptick in observed concentrations is only possible with an influence from the San Juan River.

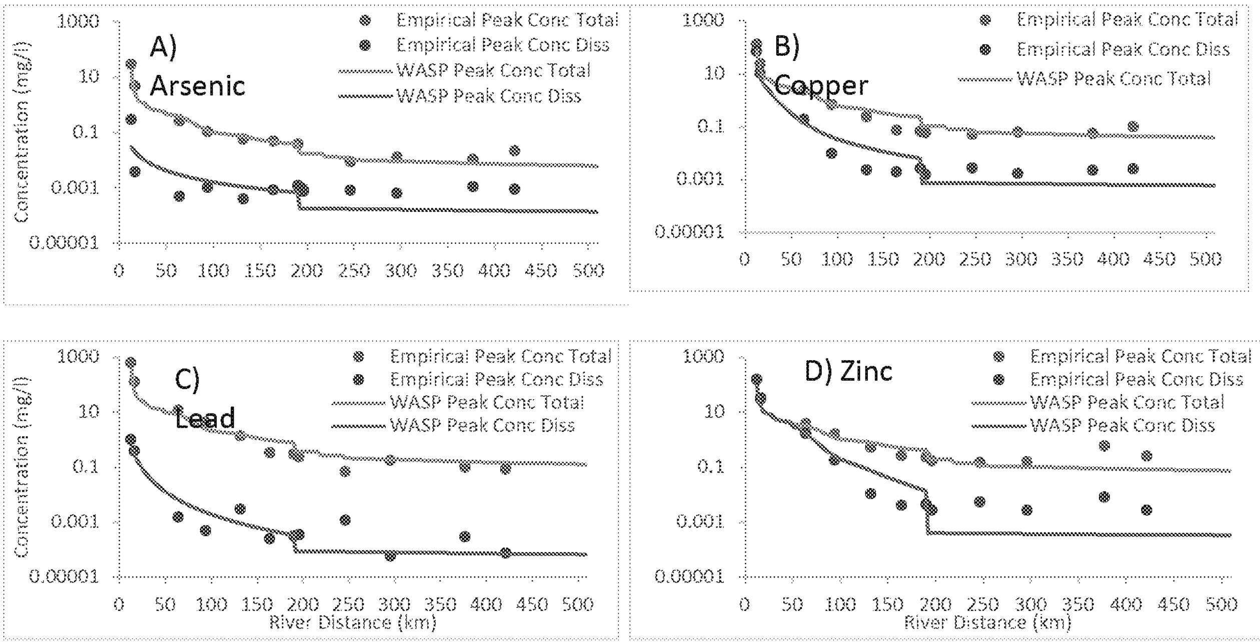

Figure 5-2. Total and dissolved simulated and observed peak concentrations for four select metals. Concentration (on log scale) plotted against river distance (km) for four metals: A) Arsenic, B) Copper, C) Lead, and D) Zinc. Upper/orange line is the peak simulated total concentration and the lower/blue line is the peak simulated dissolved concentration. The dots are calculated peak concentrations (total/orange and dissolved/blue) based on the associated empirical effort (cite). Concentrations drop orders of magnitude for all metals as the plume travels down the river. Largest drop occurs along the Animas River, with less of a decline along the San Juan River. The dissolved peak concentrations for arsenic and lead are orders of magnitude smaller than the total peak concentrations. Arsenic and lead are predominantly present as particulates upon immediately entering the Animas River. This suggests that they precipitated quickly and higher upstream. Copper and Zinc start out predominantly dissolved. Moving downstream, copper precipitates first and zinc precipitates second. The separation between total and dissolved becomes more pronounced moving down the river. These results align with the biogeochemistry that shows the order of sorption of As>Pb>Cu>Zn as a function of increasing pH.

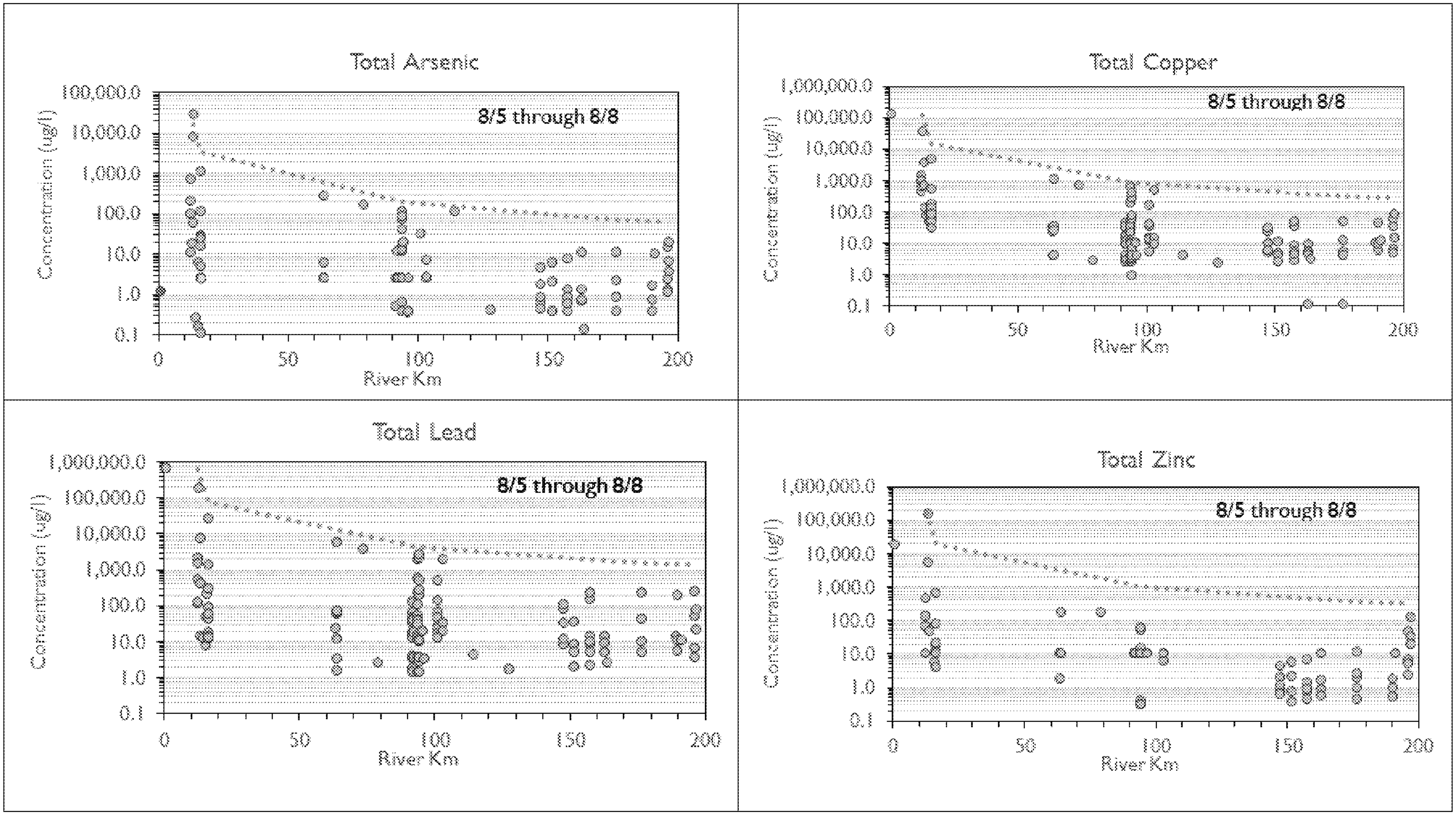

Figure 5-3. Total water concentrations of samples collected during plume passage (August 5 – August 8) in the Animas River. Dates were selected to represent maximum concentrations. Four individual metals are shown. Orange dotted line indicates maximum likely concentration based on initial concentration at Cement Creek that would occur with dilution from incoming flow between each location. Observed metals were near maximum expected in first 100 km of plume travel, except zinc which declined more rapidly.

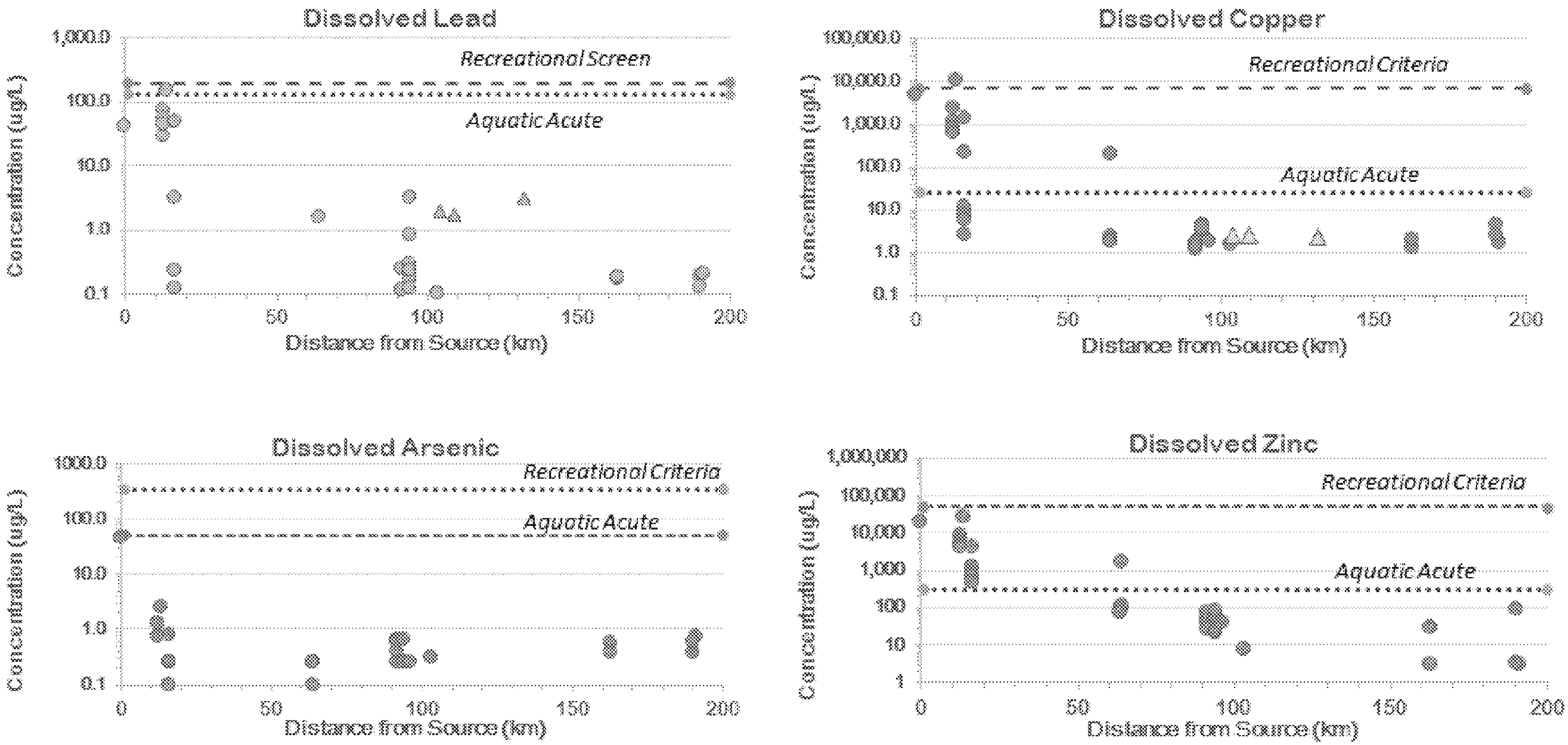

Figure 5-4. Dissolved water concentrations of samples collected during plume passage (August 5 – August 8) in the Animas River. Dates were selected to represent maximum concentrations. Four individual metals are shown. Orange dotted line indicates maximum likely concentration based on initial concentration at Cement Creek that would occur with dilution from incoming flow between each location.

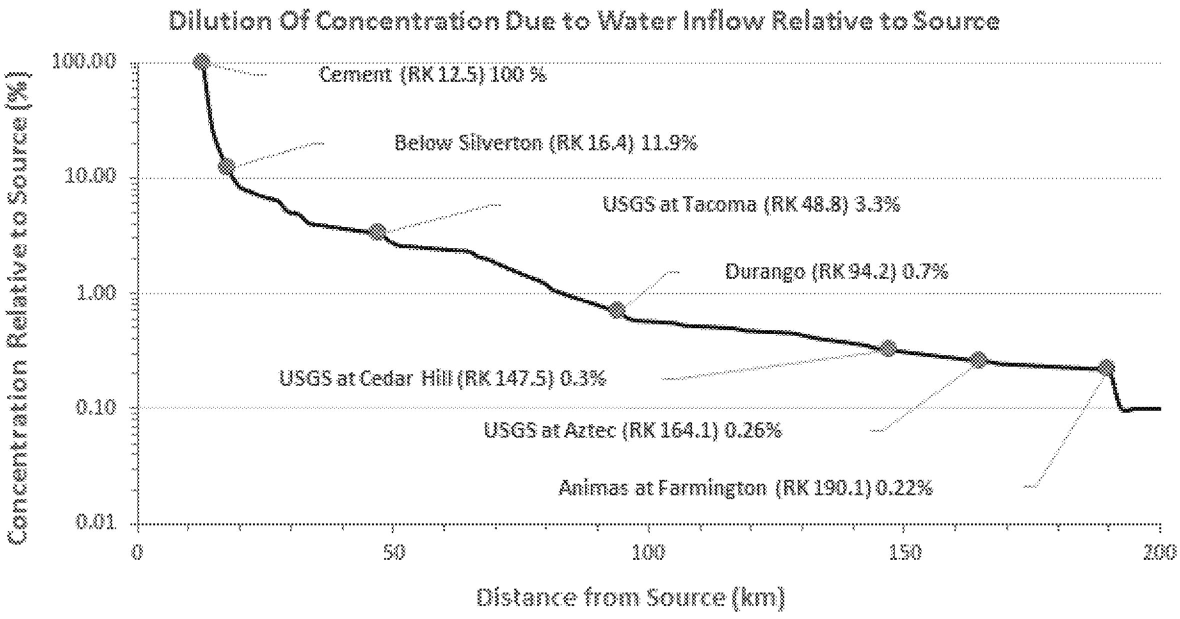

Figure 5-5. Relative change in plume concentration with movement of the Gold King plume through the Animas River. Dilution would naturally reduce metals concentrations as the river flowed and gained fresh water from incoming tributaries. The relative percent of the peak concentration is plotted versus river distance. The concentration drops rapidly as the plume enters the Animas River from Cement Creek (to 12%) due to the large volume of water it mixes with. The concentration continues to decline as it travels downstream, reaching 0.5% of the initial concentration after mixing with the San Juan River.

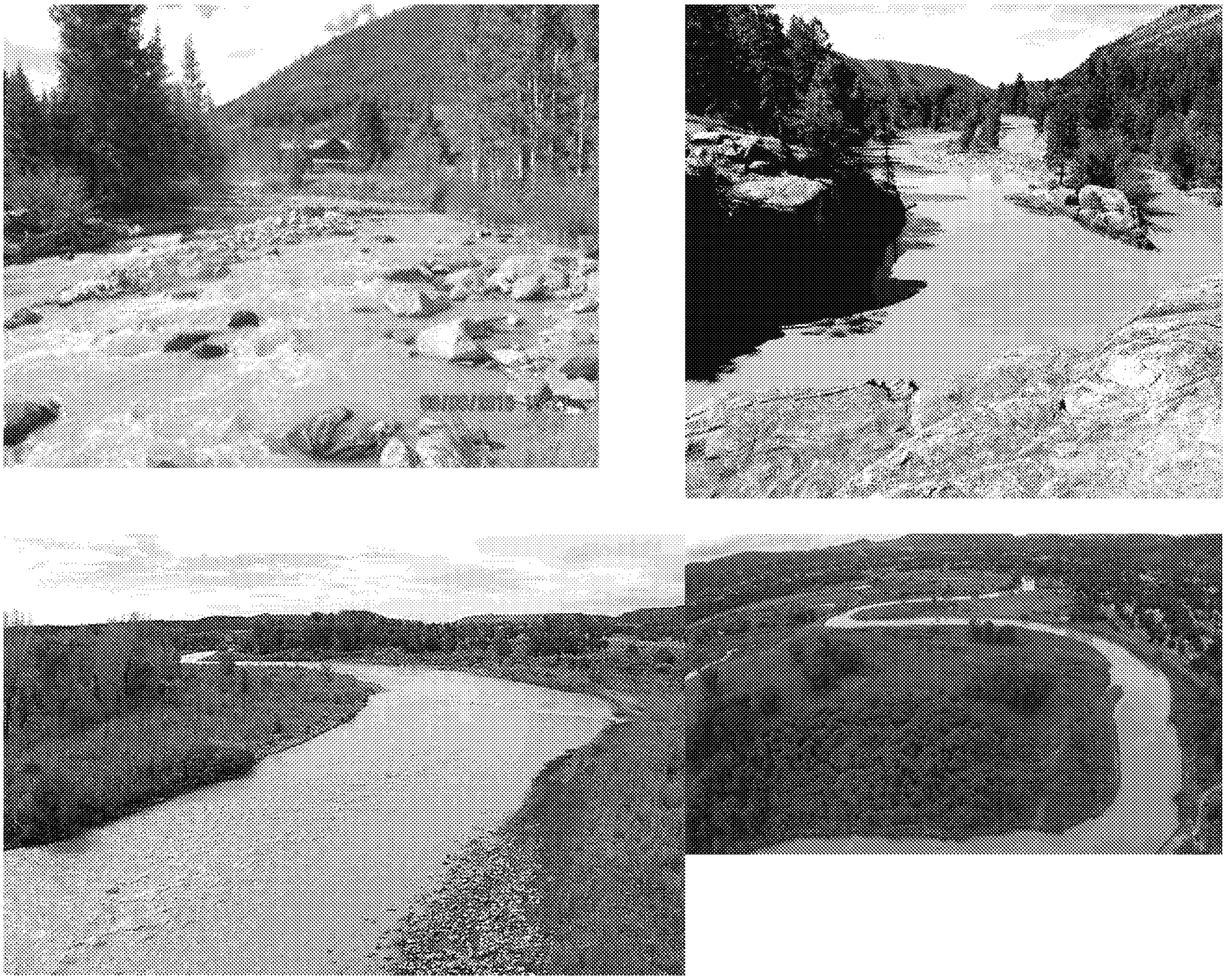

Figure 5-6. Photographs of the colored water at various locations in the Animas River. Geochemical reactions of metals within the Gold King plume occurred as the acidity of the slug neutralized as the Animas and plume mixed. Aluminum, iron, and manganese hydroxides formed creating the intense yellow color observed throughout the Animas River.

Table 5-2. The abiotic oxidation reactions of iron (Fe^{+2}) occur significantly more rapidly as pH increases. When pH in the plume was less than 4, reactions could take years (e.g. Cement Creek). The reaction could take 30 days in the pH range of 5 and hours in pH > 6. In Cement Creek, pH probably ranged from 2 to 4 (red field), so abiotic Fe^{2+}-oxidation half-life likely was years to decades, effectively yielding no ferric Fe during the hours-long transit from Gold King Mine down Cement Creek to the Animas River. In the Animas River, pH likely dominantly ranged from 6 to 8 (green field), so abiotic Fe^{2+} oxidation half-life likely was seconds to hours, and probably mostly in the seconds to minutes range shortly after the release waters mixed with the Animas water. Consequently, Fe^{2+} in the release waters likely oxidized to Fe^{3+} quickly in the Animas River. For more discussion see Appendix C.

pH (su)	$T_{1/2}$
0	65.89 years
1	65.89 years
2	65.84 years
3	61.01 years
4	7.32 years
5	30.05 days
6	7.22 hours
7	4.33 minutes
8	2.60 seconds
9	0.03 seconds

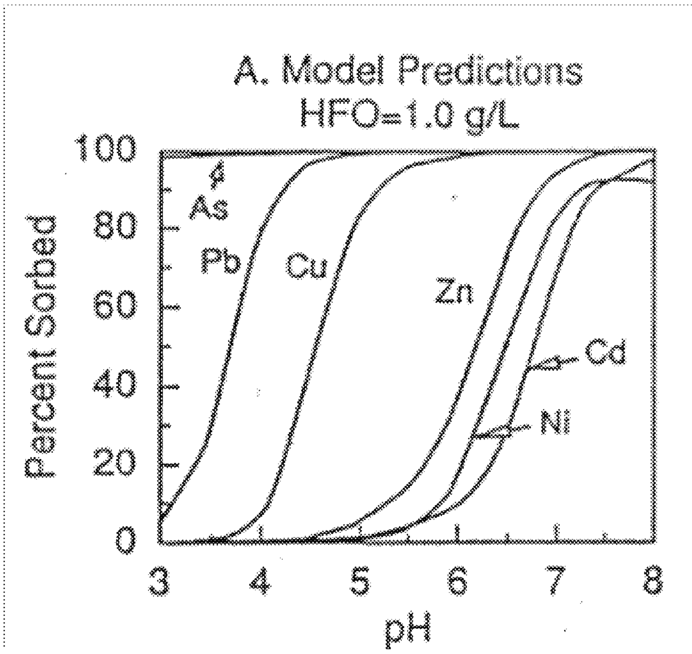

Figure 5-7. Metal sorption curves. Trace metals sorb into the oxide solids as a function of pH as a primary variable and concentrations as a secondary factor. The general pH range of sorption of dissolved to solid forms of individual metals at higher concentration of oxides is shown (from Smith 1998). Arsenic and lead sorb to solids in the pH range of 3-4, while Zn sorbs between 5-8, other metals also sorb over a relatively narrow range pH (referred to as the "sorption edge"). The Gold King Mine plume passed through these pH ranges as it travelled within the Animas River.

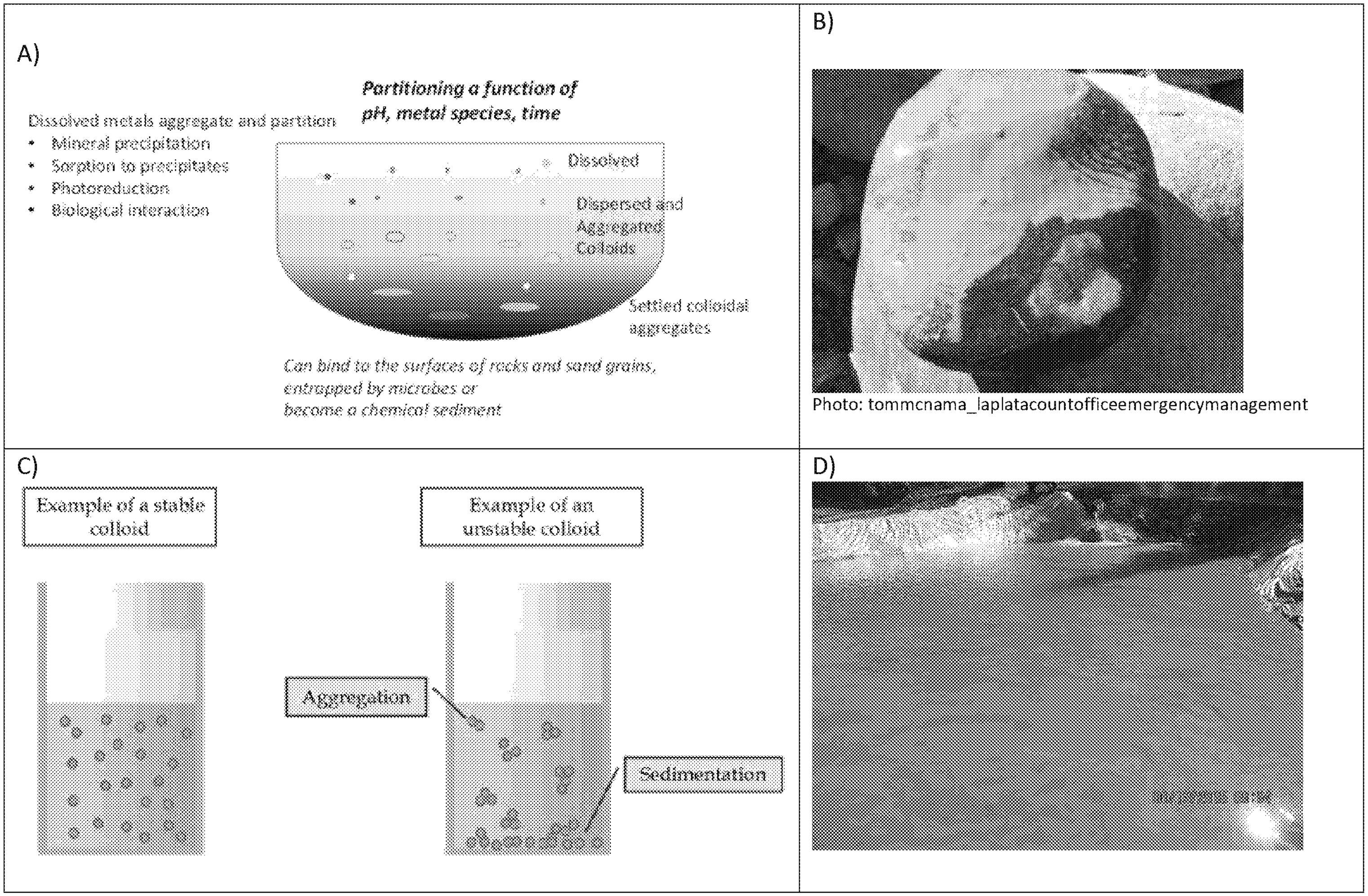

Figure 5-8. Characteristics of the plume precipitates. The iron and aluminum hydroxides are colloids, which are solid particles of size range up to 10 μm that are suspended in the acidic water. Fully dispersed colloids are like milk or paint, and can easily be suspended or get transported by the flows in the river and may have "painted" rocks as shown in B. The particles can also aggregate and settle due to electrical changes among particles (C and D) and settle to the streambed. All are termed "yellow boy" and represent a mix of oxides. These oxides sorb trace metals into their matrix.

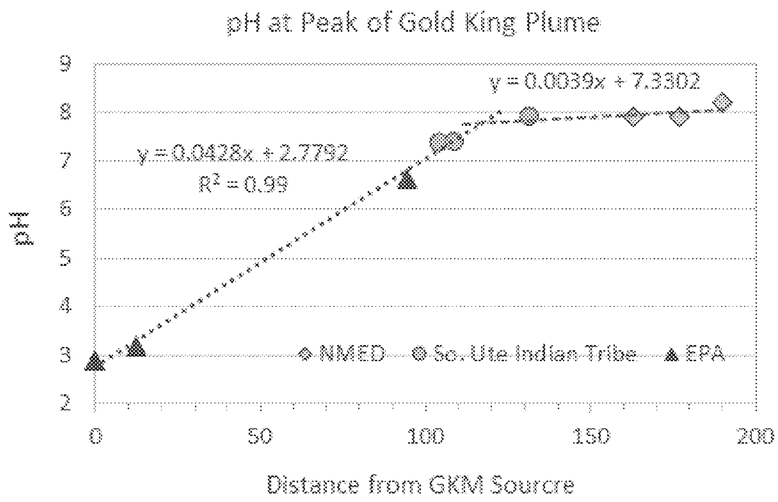

Figure 5-9. Observed pH during passage of the Gold King Mine plume at or near peak in the Animas River. pH increased approximately linearly as the plume travelled through the upper Animas. The river approached background pH at approximately 120 km from source (within SUIT reservation). Downstream of this point, pH dipped slightly as the plume as the front of the plume passed, but most chemical reactions were primarily completed by this time. According to Table 5-2, reactions would be slow to about river kilometer 40, and rapidly increase for 64-100km.

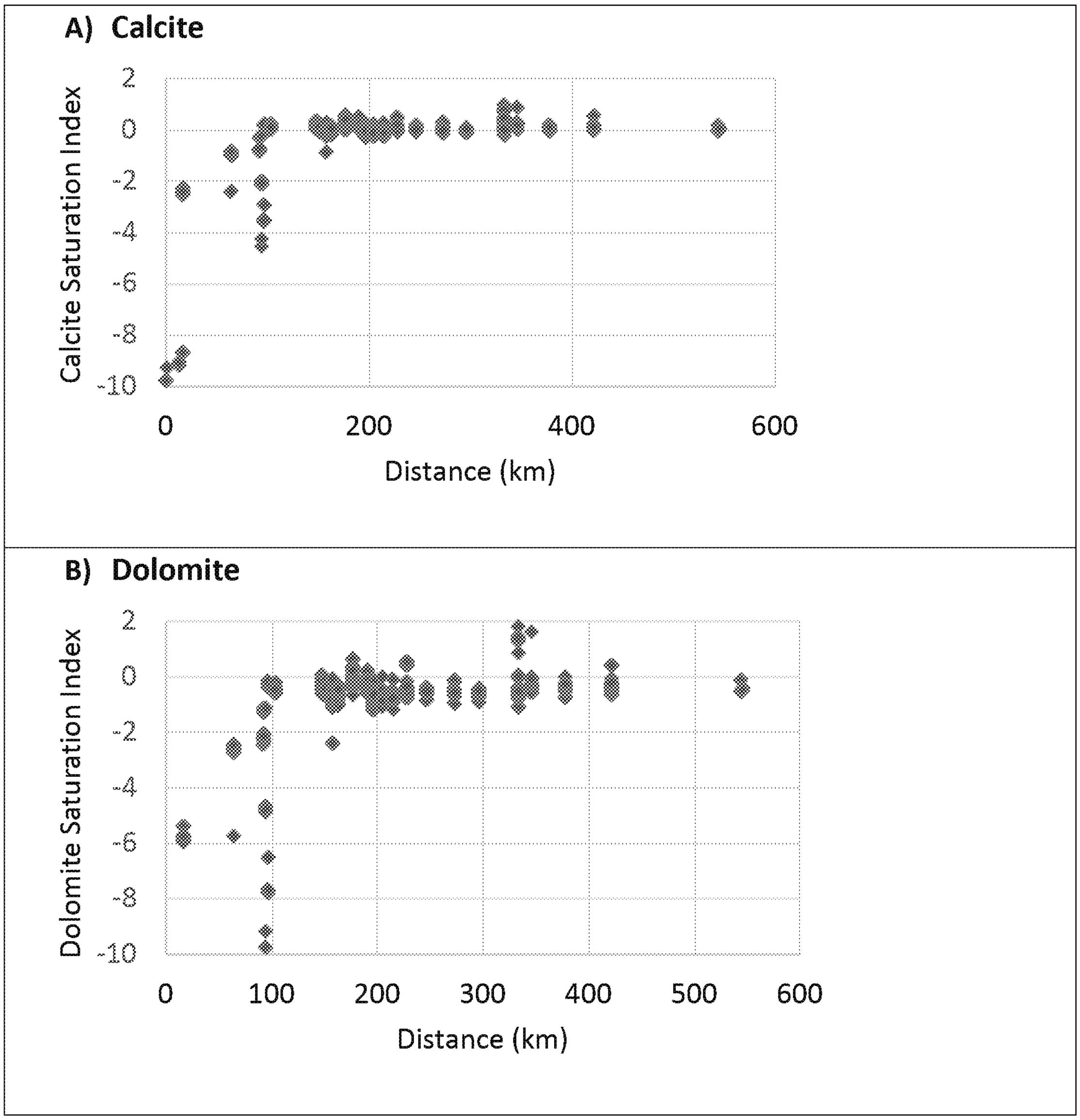

Figure 5-10. Saturation Indices (SIs) for calcite (A) and dolomite (B) vs distance from Gold King Mine. An SI of zero indicates saturation with the mineral phase. Negative SI values indicates that the water is undersaturated with the mineral. See Appendix C for details on this analysis.

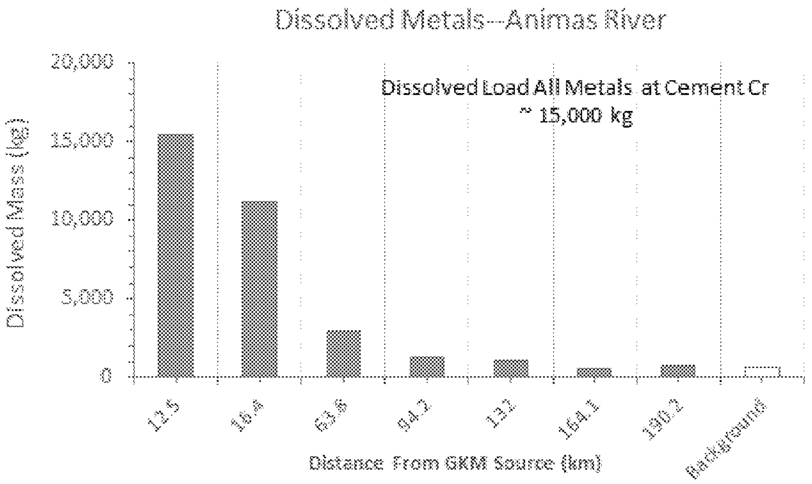

Figure 5-11. Dissolved load of metals (kg) as the Gold King plume as the plume passed locations in the Animas River. Dissolved mass transitioned to colloidal/particulate form. The mass of dissolved metals input from Cement Creek to the Animas River was estimated at 11,000 kg. Summing total metals, the mass of dissolved decreased with distance declining to background levels in the Animas before joining the San Juan at Farmington (river kilometer 190.2). Most of the transition occurred by Durango at river kilometer 94.2

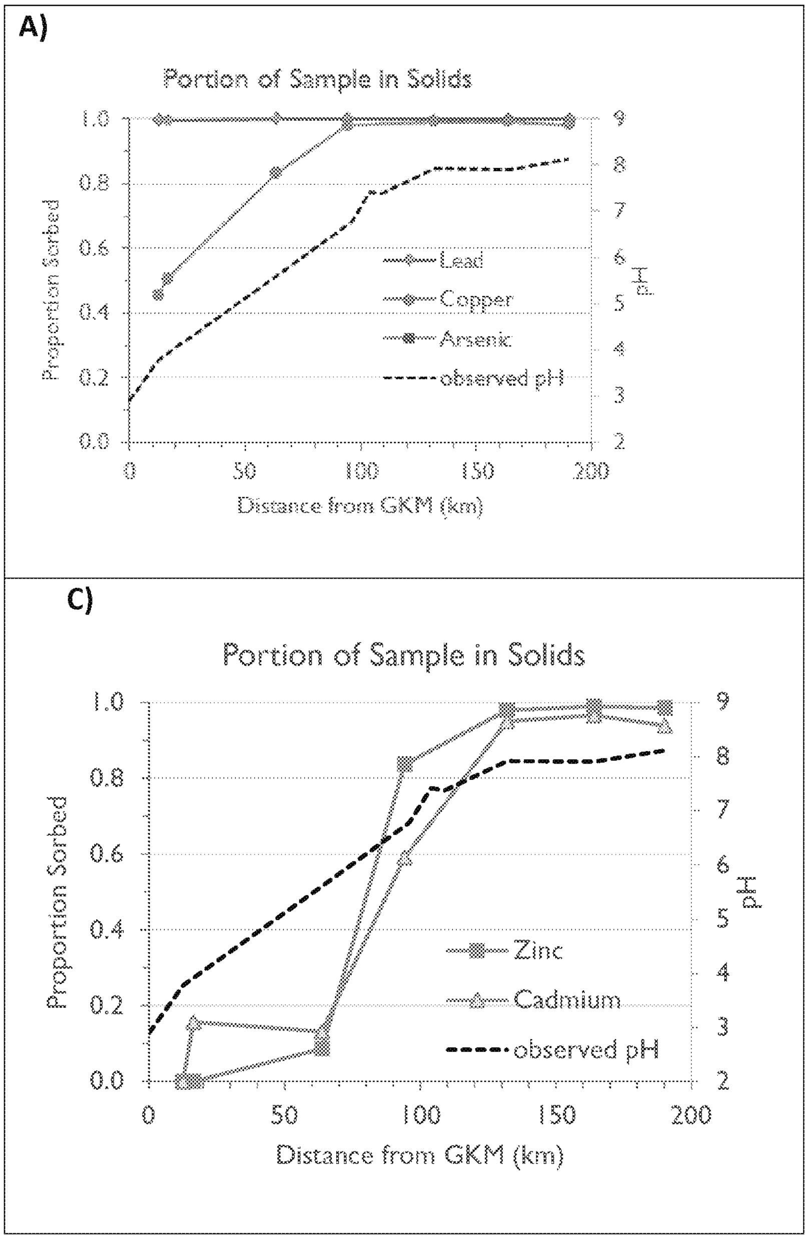

Figure 5-12. Sorption of metals relative to pH in the Animas River. The sorption of five metals relative to observed pH is shown in A) lead, copper, arsenic and C) cadmium and zinc. pH observed in the river is translated to distance based on Figure 5-9 to show change in proportion to colloidal (% sorbed) with travel of the plume. Lead, copper, and arsenic sorb to solids at lower pH and one mostly sorbed by Baker's Bridge (river kilometer 64). Zinc and cadmium sorb at higher pH and were not fully sorbed until Aztec, NM (river kilometer 164.1).

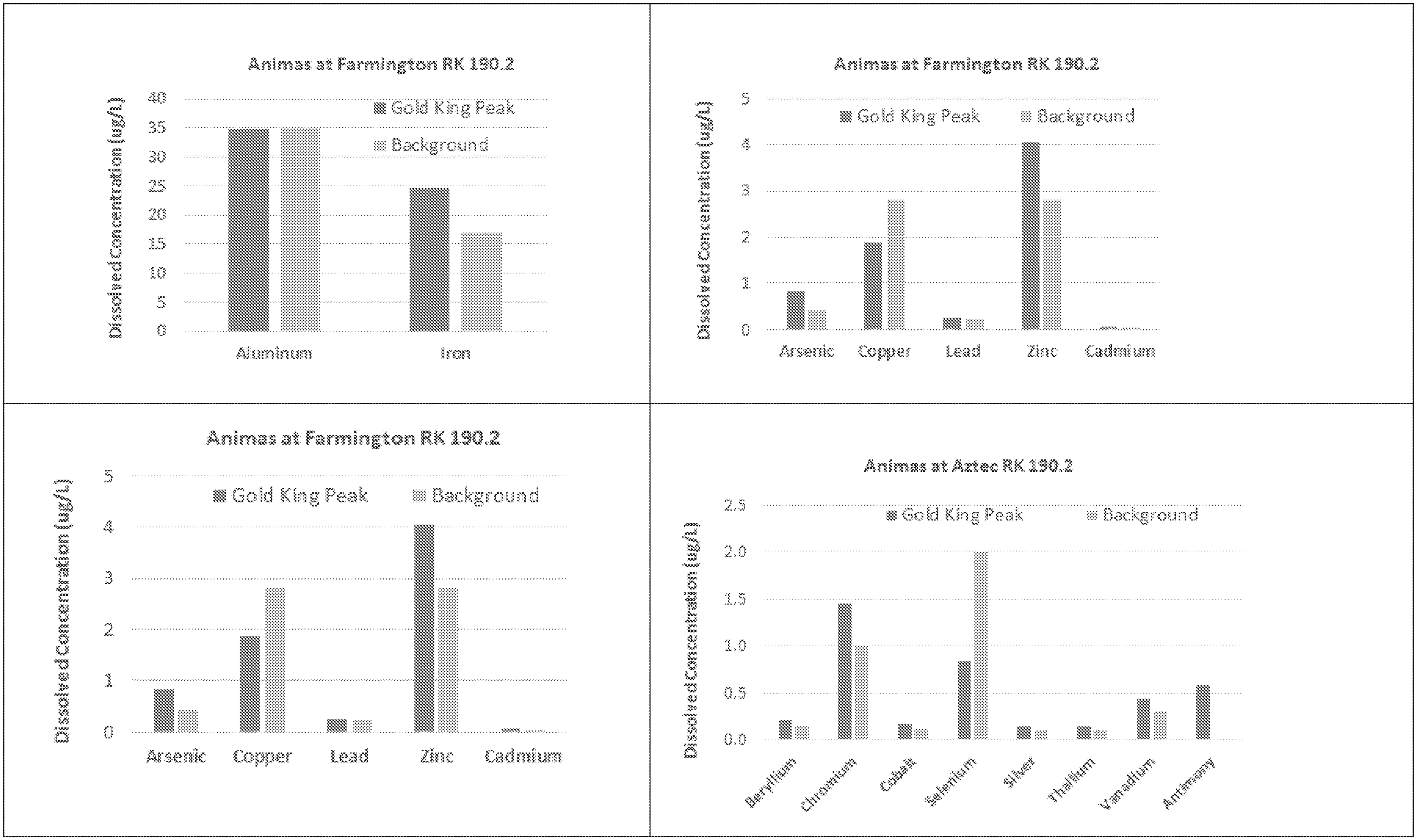

Figure 5-13. Comparison of dissolved metal concentrations at the peak of the Gold King plume and estimated background concentrations in the lower Animas at Farmington before entering the San Juan River. Concentrations of dissolved metals are low and virtually the same as background. Iron and zinc were somewhat elevated above background.

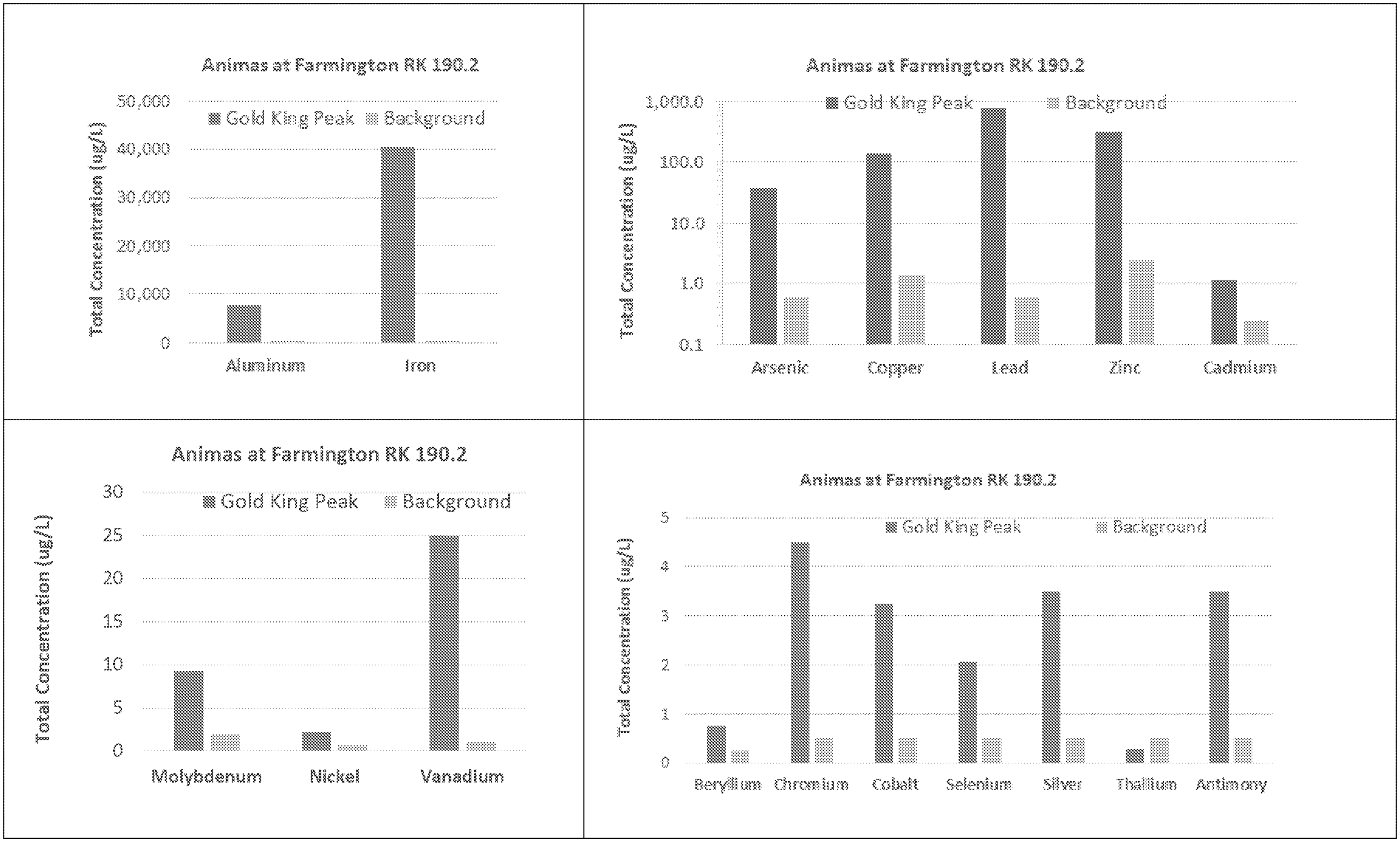

Figure 5-14. Total concentrations of Animas at Farmington relative to background. Comparison of total metal concentrations at the peak of the Gold King plume and estimated background concentrations in the lower Animas at Farmington before entering the San Juan River. Concentrations of total metals made up primarily of colloidal/particulates was significantly elevated for most metals. Iron and aluminum were particularly high, as was lead, copper, arsenic, and zinc.

Animas/San Juan confluence at low flow	Animas/San Juan confluence during Gold King plume
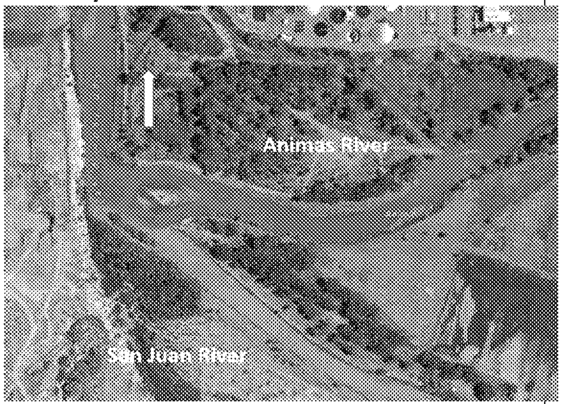	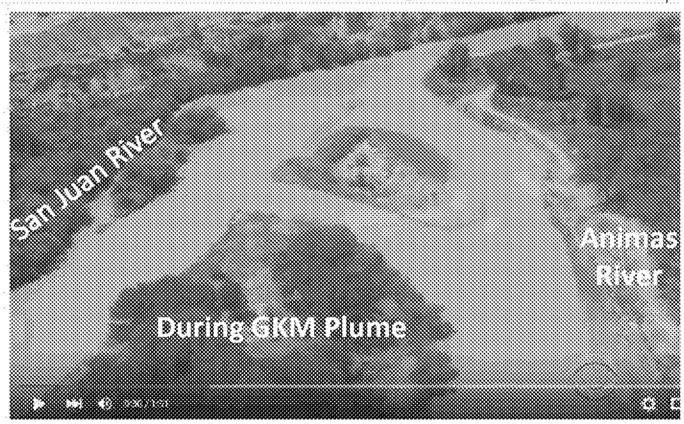
Photo: GoogleEarth	Photo:

Figure 5-15. Junction of the Animas and San Juan Rivers. A) Google Earth image of confluence at low flow. The Animas normally enters in low flow conditions with somewhat higher flow and less turbid waters. The Navajo Dam 74 km upstream of the junction controls flow in the San Juan River. B) During the passage of the Gold King plume, flow in both rivers was relatively higher than normal for the time of the year and about equal in volume. The plume was evident in the Animas, while the sediment load in the San Juan was very turbid that masked the plume visibility.

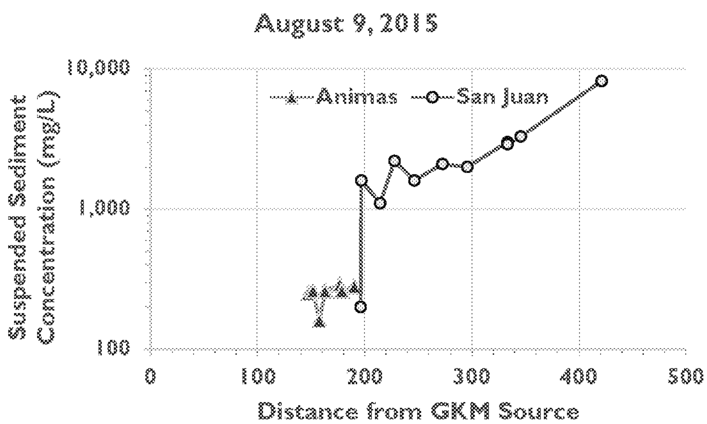

Figure 5-16. Suspended sediment during Gold King plume. The confluence of the Animas and San Juan Rivers is located at 193 distance. Total suspended sediment was measured at a number of locations in the Animas and San Juan Rivers as the plume passed. Suspended sediment measured by 10-fold when the Animas joined the San Juan at Farmington. Total suspended sediment continued to increase as the Animas flowed westward.

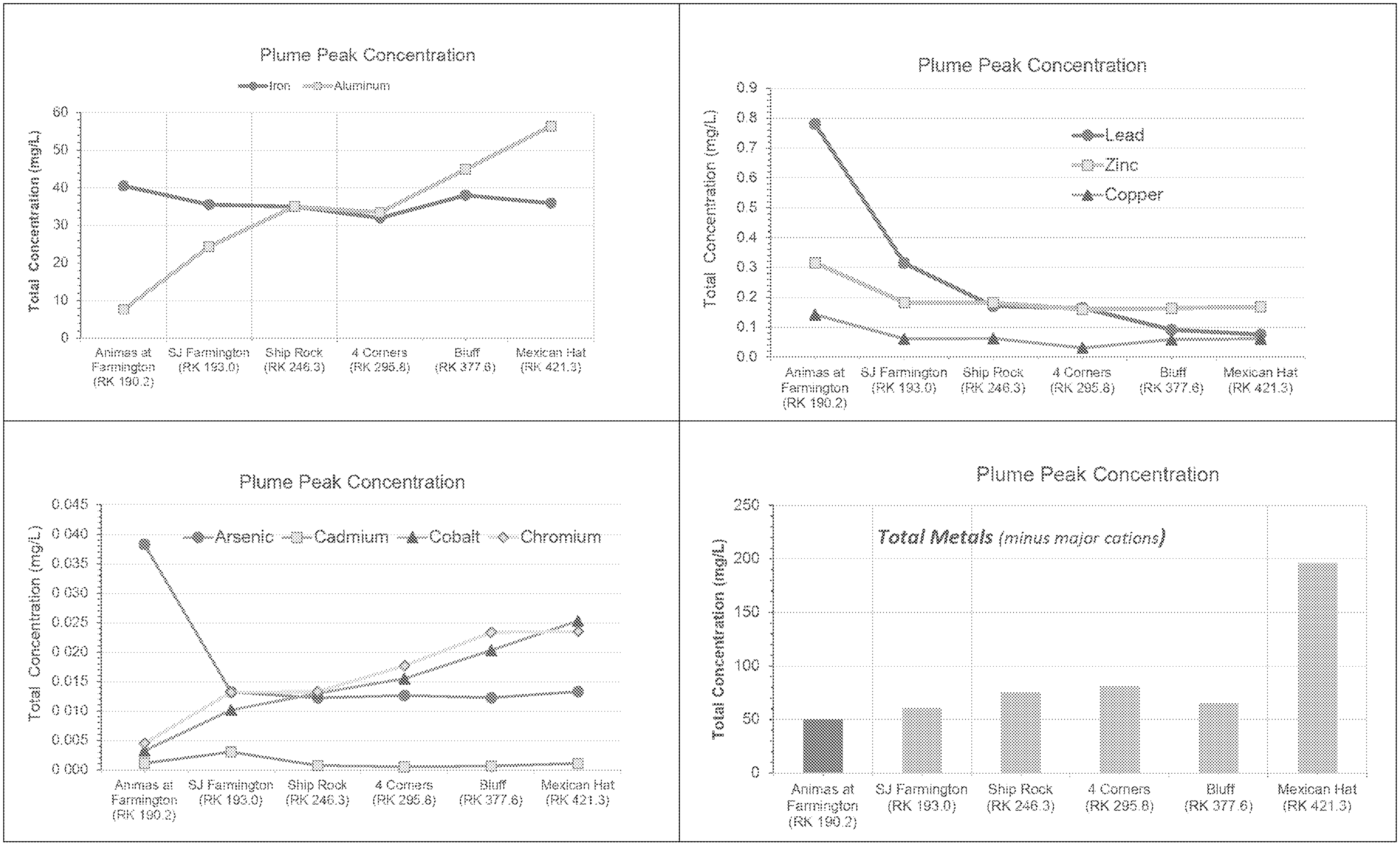

Figure 5-17. Total metals concentrations in the San Juan River. Estimated metals peak concentrations in the San Juan River during the Gold King plume. Also shown is the concentration in the Animas River prior to flowing into the San Juan. Total concentration of metals was the same in the San Juan as the Animas, although flow doubled. This suggests that, generally, metals concentrations were equal in the two rivers. Some metals decreased on joining the San Juan (lead, zinc, copper, arsenic) while some increased (aluminum, chromium, cobalt).

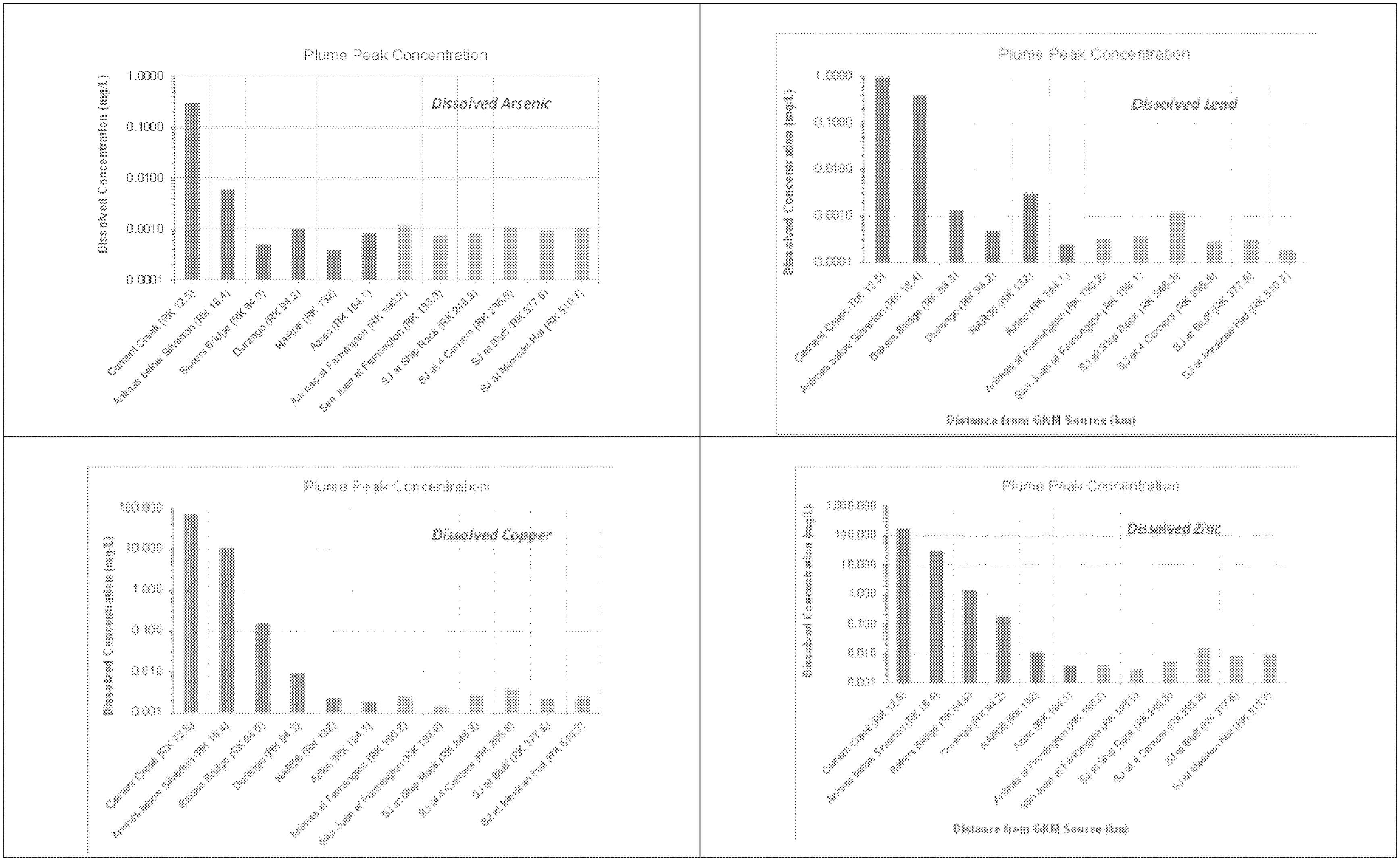

Figure 5-18. Peak dissolved concentration as Gold King plume passed through for arsenic, lead, copper and zinc.

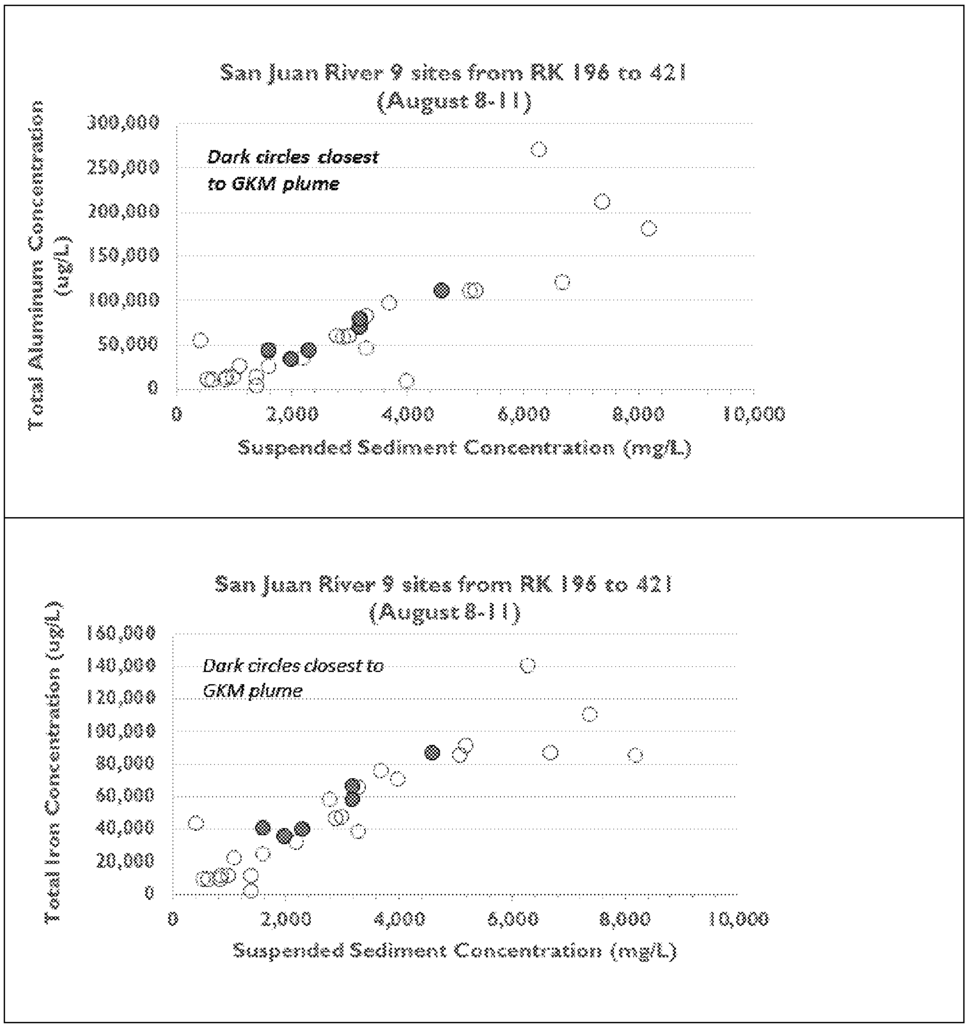

Figure 5-19. Aluminum and iron related to sediment. Relationship of total aluminum and iron with suspended sediment concentration in the San Juan River in samples collected during the passage of the Gold King plume. These values are typical concentrations. Aluminum was about 2.5% and iron about 5% of the sample.

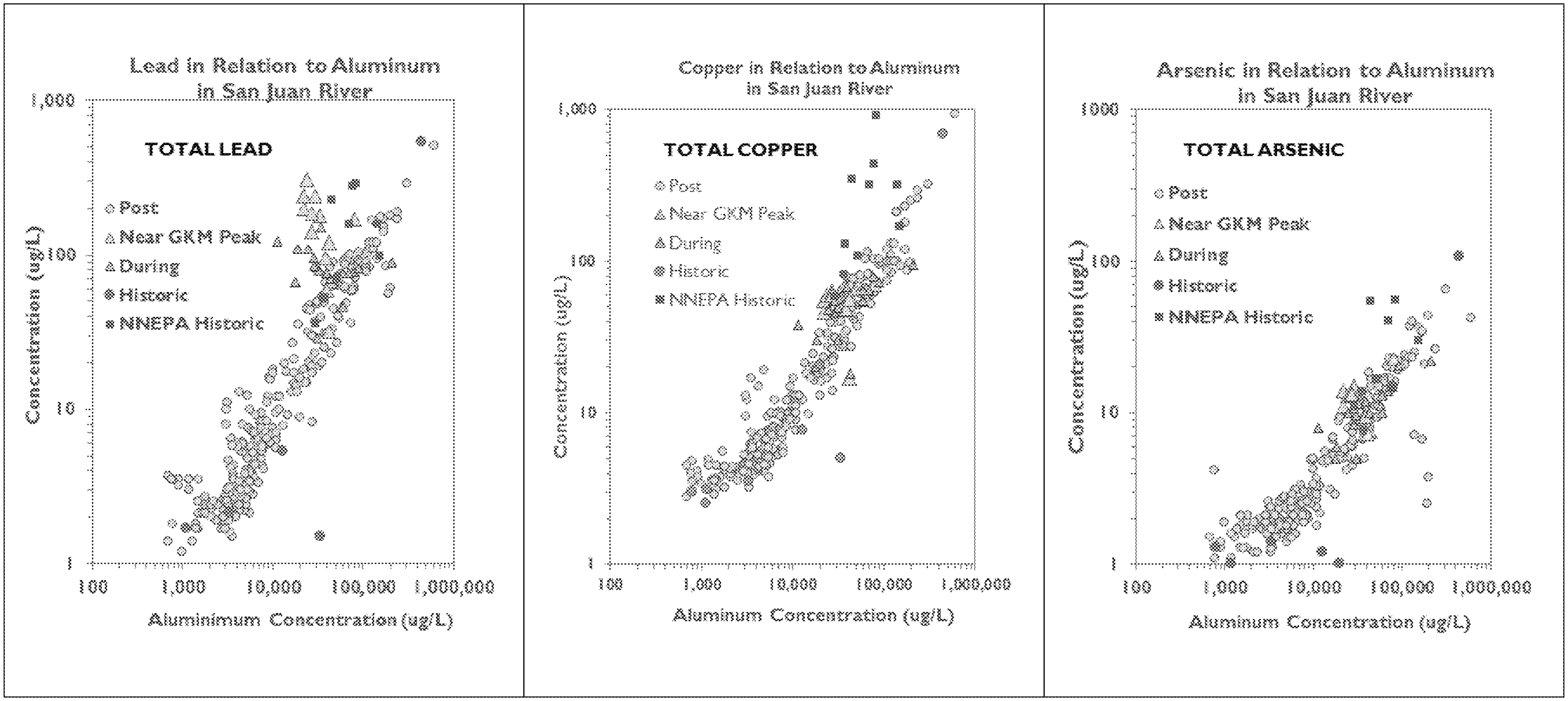

Figure 5-20. Correlation analysis of metals. Relationship between individual trace metals and aluminum (total) in water samples collected throughout the San Juan River during the Gold King plume and through October 2015. There is a strong relationship between trace metals with aluminum. A similar relationship occurs with iron (not shown). Plume samples are identified as gold triangles. Blue squares are Navajo Nation historic data and red circles are EPA historic data. Aluminum ranged between 10,000 to 100, 000 µg/l. The plume samples were relatively elevated in lead (expected < 80 µg/l; observed 8-300). Copper and aresenic were generally within their expected range suggesting they were not elevated within the San Juan River during the plume. Concentrations were highest in late fall storms that elevated suspended sediment.

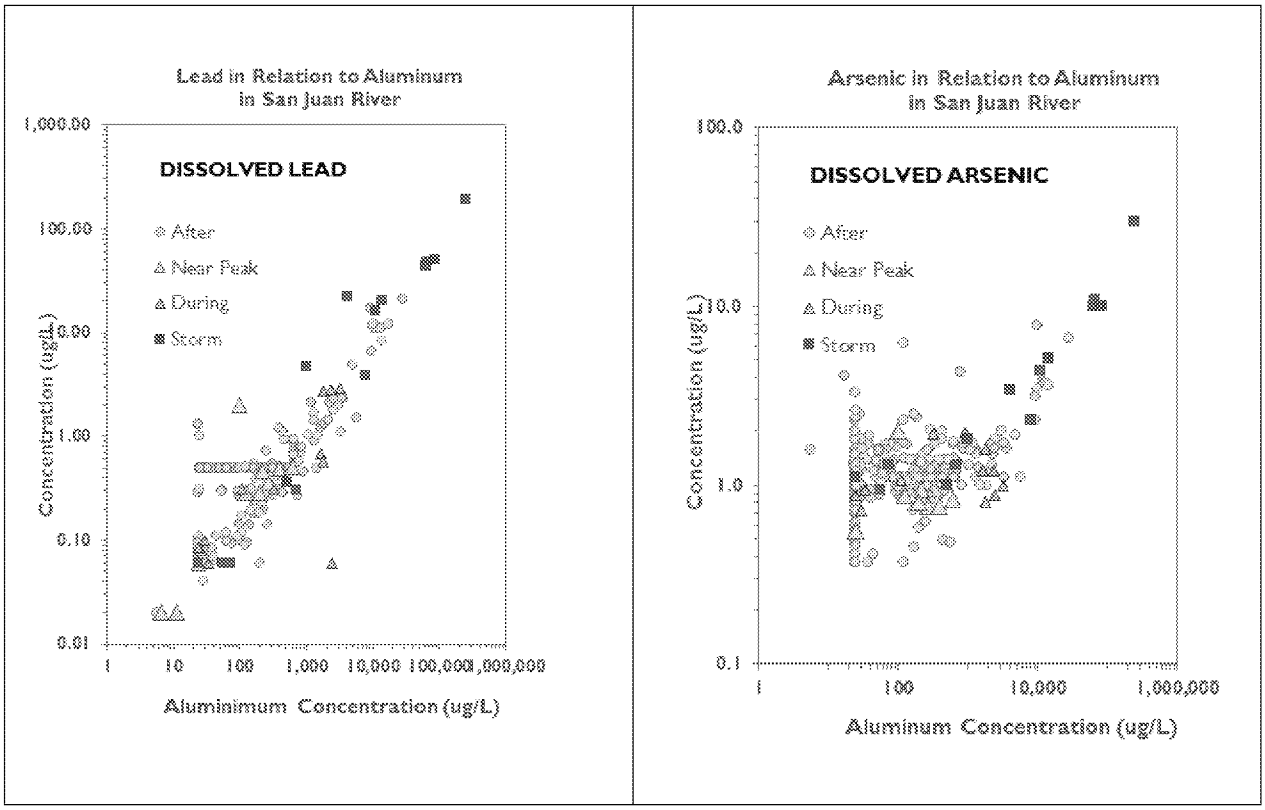

Figure 5-21. Relationship between dissolved lead and aluminum. There was no elevation of plume samples relative to their expected range as observed with total concentration.

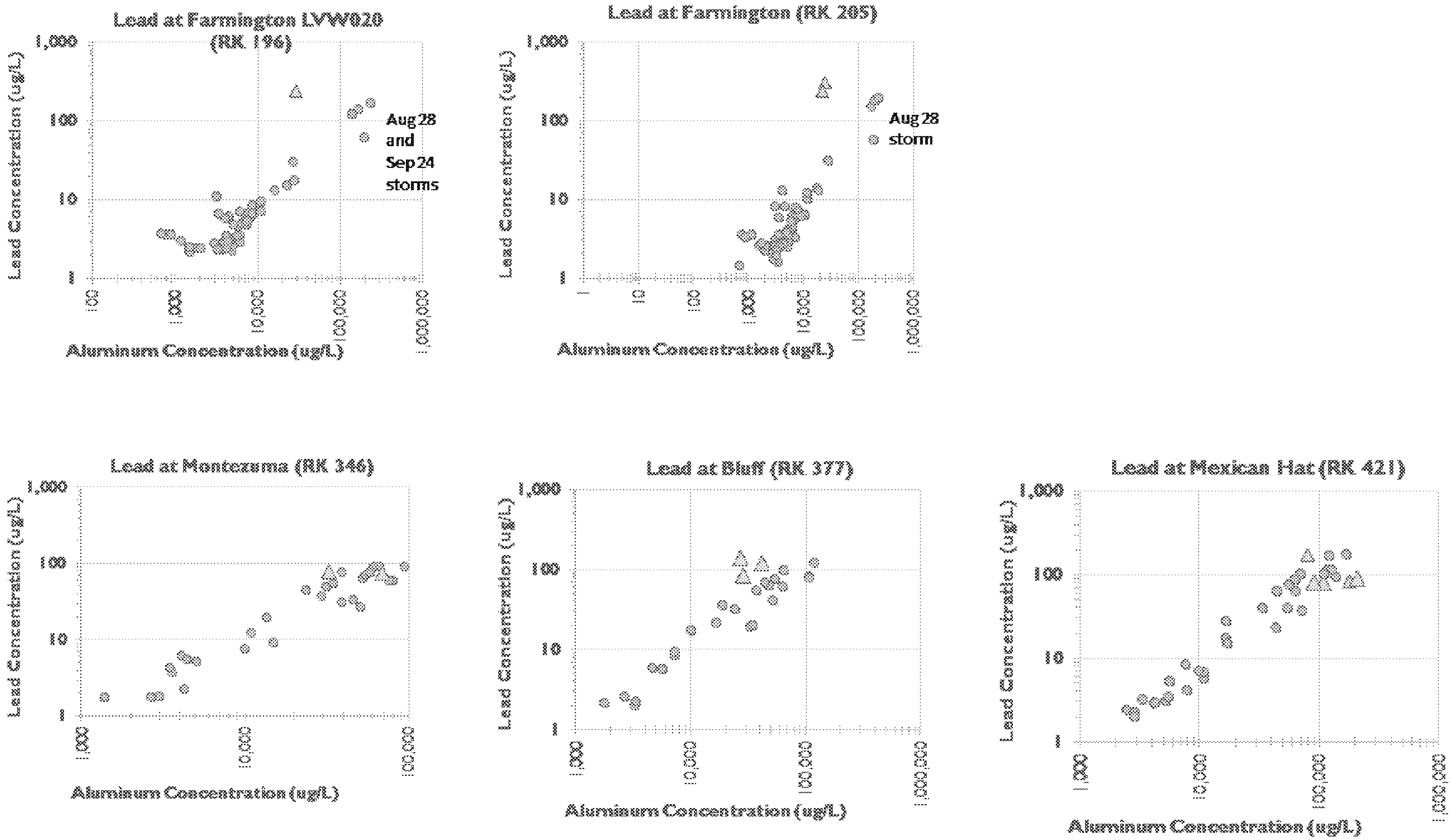

Figure 5-22. Total lead correlation with aluminum at individual location on the San Juan River. Total lead relative to aluminum in samples collected as the Gold King plume passed (gold triangles) and in the following month at selected locations. Lead was elevated relative to expected concentrations in Farmington to 4-Corners sites, but was close to background at Montezuma (river kilometer 346), Buff (river kilometer 377), and Mexican Hat (river kilometer 421).

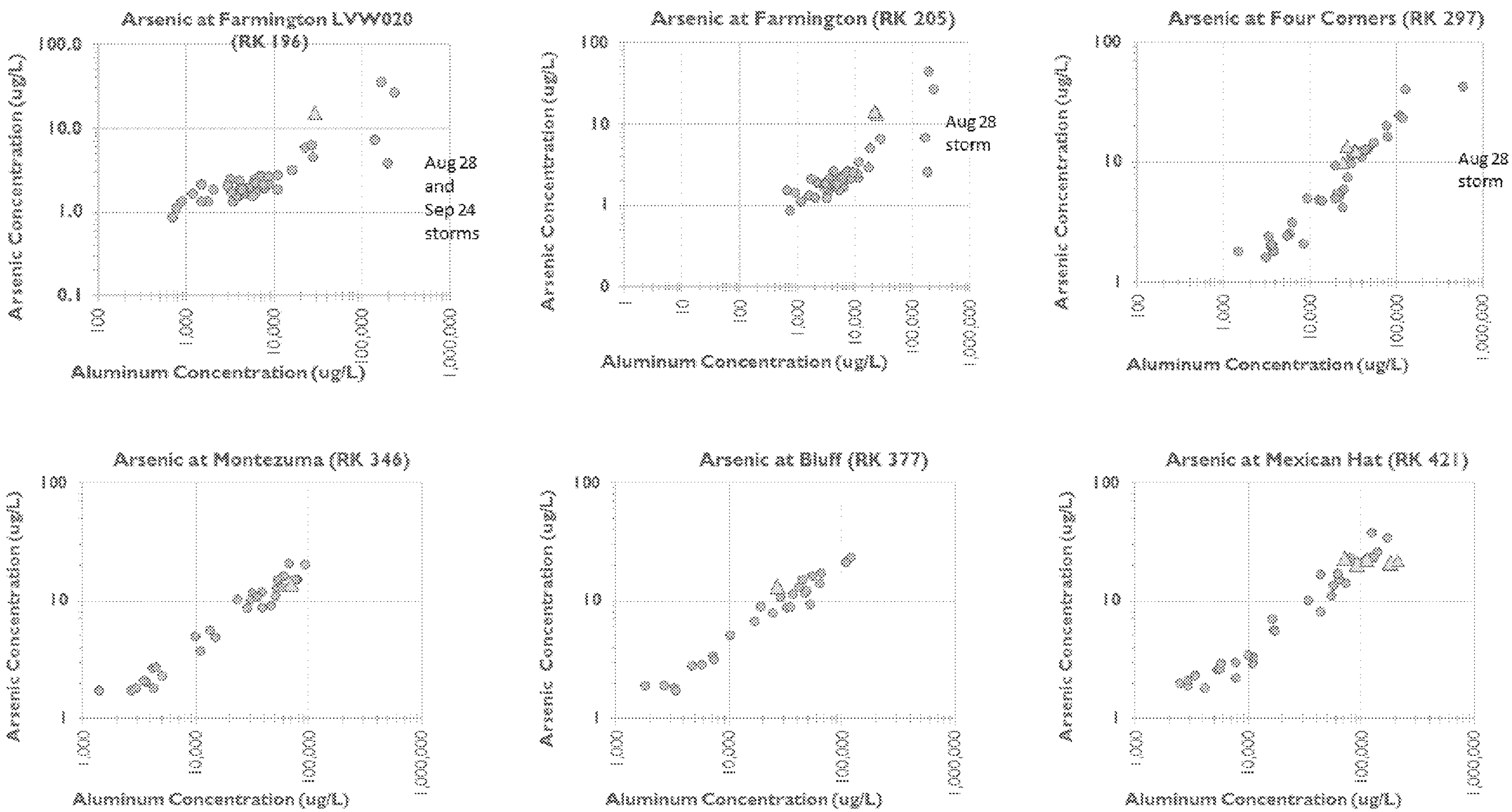

Figure 5-23. Total arsenic correlation with aluminum at individual location on the San Juan River. Arsenic was somewhat elevated in Farmington but was within expected range at locations further downstream.

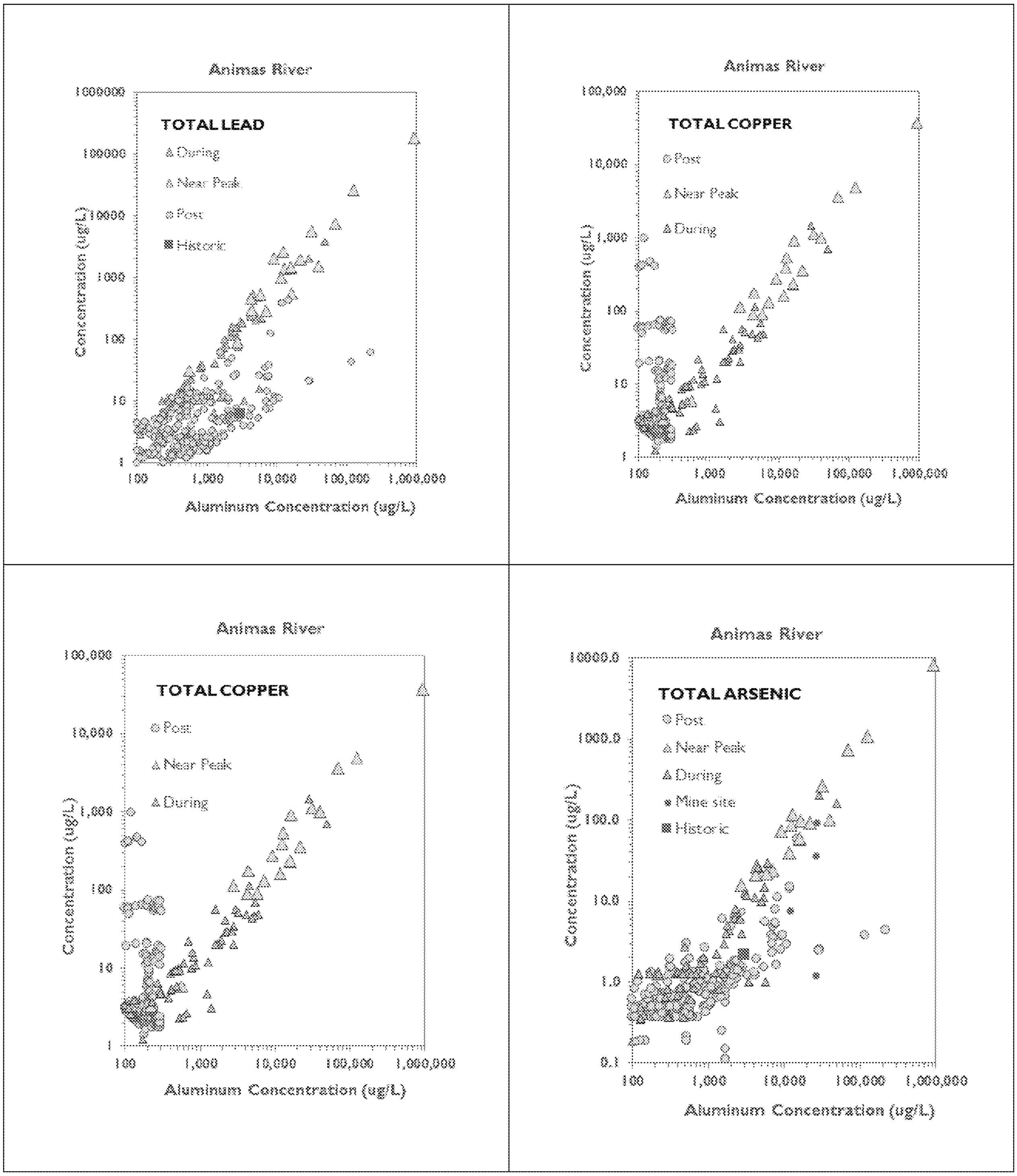

Figure 5-24. Relationship between individual trace metals and aluminum in the Animas River. Gold triangles are samples collected during the plume and blue circles are post-event through October. A relationship exists in the Animas, but aluminum and many trace metals all exceeded previously observed concentrations. The Gold King plume was unique in the data record relative to aluminum and trace metal concentrations. Post-event samples were generally lower than historic concentrations.